Critical Technology Events in the Development of Selected Army Weapons Systems

A Summary of *Project Hindsight Revisited*

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Center for Technology and National Security Policy

September 2006

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Critical Technology Events in the Development of Selected Army Weapons Systems. A Summary of Project Hindsight Revisited**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Defense University,Center for Technology and National Security Policy,Fort Lesley J. McNair BG 20,Washington,DC,20319**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**33**	

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Acknowledgments. The *Project Hindsight Revisited* series of studies would not have been possible without the contributions of a great many people. We have done our humble best to acknowledge in our foregoing reports those who assisted us in our research. Here, we would like to re-emphasize our gratitude for the efforts of two of these people: Dr. Thomas Killion, the Army S&T Executive, who saw the benefit of looking back at key Army weapons systems for insights that would be helpful in managing S&T in today's environment; and Al Sciarretta, who ably supported the entire *Hindsight Revisited* project and gave us valuable insight based on his experience as an active duty Army officer. We would also like to express our appreciation to our colleagues at the Center for Technology and National Security Policy, and to its director, Dr. Hans Binnendijk, for their ongoing support.

Defense & Technology Papers ***are published by the National Defense University Center for Technology and National Security Policy, Fort Lesley J. McNair, Washington, DC. CTNSP publications are available online at*** **http://www.ndu.edu/ctnsp/publications.html.**

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I. Introduction: *Project Hindsight Revisited* and the Critical Technology Event Concept

In 2004, Dr. Thomas Killion, the Army Science and Technology (S&T) Executive, requested a series of reports detailing technology development for selected Army weapons systems. Dr. Killion was interested in studying the genesis of successful, fielded systems to gain insight into common factors that promoted technology development and integration. He was inspired in part by a similar study conducted by the Department of Defense (DOD) in the 1960s, called *Project Hindsight*.[1] Dr. Killion hoped that the findings of the studies could help guide decisions in managing the Army S&T portfolio.

Our *Hindsight Revisited* reports covered four Army weapons systems. We first studied the development of the Army's premier ground combat vehicle, the Abrams main battle tank.[2] We followed that study with a paper on the development of the Apache attack helicopter.[3] We then covered two man-portable missile systems in a third report: the Stinger antiaircraft missile and the Javelin antitank missile.[4]

This report collects and summarizes the findings from these three studies. Included here are findings related to the contributions of the Army's in-house laboratories, the Program Managers' (PM) offices, and industry. We compare these findings to the findings from the original *Project Hindsight*. The report then offers recommendations, based on our findings for the four systems, for managing today's Army science and technology work. The paper concludes with commentary on two issues of current interest in today's environment: the problem of attracting and retaining talented technical staff for the government's in-house laboratories, and the implications of recent changes in the acquisition process, as seen in the way the Future Combat Systems (FCS) program is being developed. Before embarking on our analysis, findings, and recommendations, however, it is useful to define critical technology events, the key unit of analysis in the *Hindsight Revisited* reports, and place them in the context of the overall innovation process.

Our three *Hindsight* papers had a common unit of analysis: the critical technology event, or CTE. CTEs are ideas, concepts, models, and analyses, including key technical and managerial decisions, that had a major impact on the development of a specific weapons

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[1] Office of the Director of Defense Research and Engineering, *Project Hindsight: Final Report* (Washington, DC: Office of the DDRE, 1969).
[2] Chait, Lyons, and Long, "Critical Technology Events in the Development of the Abrams Tank: Project Hindsight Revisited," *Defense and Technology Paper 22* (Washington, DC: Center for Technology and National Security Policy, December 2005).
[3] Chait, Lyons, and Long, "Critical Technology Events in the Development of the Apache Helicopter: Project Hindsight Revisited," *Defense and Technology Paper 26* (Washington, DC: Center for Technology and National Security Policy, February 2006).
[4] Lyons, Long, and Chait, "Critical Technology Events in the Development of the Stinger and the Javelin Missiles: Project Hindsight Revisited," *Defense and Technology Paper 33* (Washington, DC: Center for Technology and National Security Policy, July 2006).

system. CTEs can occur at any point in a system's life cycle, from basic research, to advanced development, to testing and evaluation, to product improvements. CTEs can even relate to concepts that were developed but that ultimately were not incorporated into the weapons system. Also, they can originate in many places: the Army's in-house laboratories, the private sector, academia, and the research and development programs of our allies. Using CTEs as hallmarks of technical advances gave us a way to focus our attention on the important factors for success. We did not attempt to capture every single technical development in a given system or to discuss its development in exhaustive technical detail.

Given the central importance of the CTE to our reports, it is worthwhile to explain the concept in greater detail and place it in the broader context of technical innovation. A useful framework for understanding the innovation process and the genesis of operationally useful advances is provided by a recent report from the National Defense University, "The S&T Innovation Conundrum," by Coffey, Dahlburg, and Zimet.[5] The authors hold that there are two distinct phases in science and technology innovation, "prospecting" and "mining" (see figure 1). Prospecting is early work that provides a fundamental scientific basis for later research. Mining is later work to develop specific systems. The prospecting phase is often not focused on a particular outcome, so the contribution to a particular military (or other) capability is low. The mining phase draws on knowledge gained in the prospecting phase to yield useful capabilities.

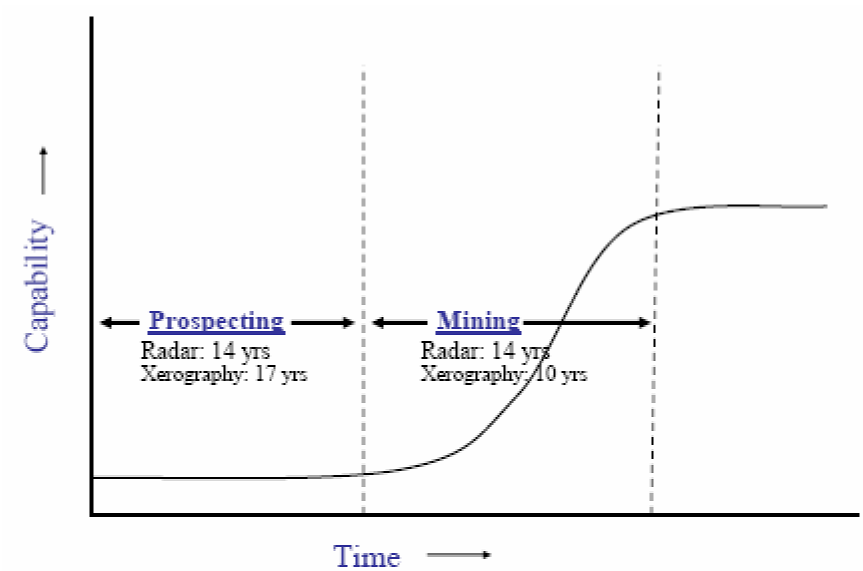

Figure 1. Prospecting and mining phases of development of two new technologies.[6]

The majority of our CTEs occurred in the mining phase, in the later stages of the basic research-to-engineering development continuum. If taken at face value, this would seem to discount basic research and suggest that the most important S&T work takes place in

[5] Timothy Coffey, Jill Dahlburg, and Elihu Zimet, "The S&T Innovation Conundrum," *Defense and Technology Paper 17* (Washington, DC: Center for Technology and National Security Policy, August 2005).
[6] Drawn from Coffey et al.

applied research, advanced development, and engineering development. This conclusion would be incorrect, for two reasons. The first relates to how we defined our CTEs and the second has to do with the foundational nature of basic research. We now discuss both.

First, we elected to count as CTEs only those things that bore on significant improvements over the predecessor systems. The Abrams was compared to the M–60 Patton tank, the Apache to the AH–1 Cobra, the Stinger to the Redeye, and the Javelin to the Dragon. We could have broadened the time horizon of our examination considerably. For example, to discuss infrared vision systems for the Abrams tank we could have looked back to the development of the quantum theory in the early 20th century and the subsequent development of solid state physics in mid-century and found CTEs all along the way. Doing so would not have shed much light on what was a critical technology in the DOD's development of the particular weapons systems, and would have shifted focus from the specific factors that have produced great improvements in the performance of the weapons systems studied in comparison to those they replaced.

Secondly, basic research need not be as non-specific and general as the above reference to quantum theory would suggest. It can be problem-driven as well as curiosity-driven. Though the DOD defines basic research as the scientific study of phenomena not related to any one specific weapons system (i.e., curiosity-driven),[7] and while there are many examples of curiosity-driven research in DOD (most clearly in the work sponsored at universities), a majority of DOD research is problem-driven. It thus bears directly on the needs of specific programs and systems. Also, even non-specific and general research is needed to lay the foundations for future advances. Someone must do the prospecting if there is to be any mining.

The importance of basic research is illustrated by figure 2, which charts the evolution of the technology associated with the M829 series of long-rod penetrators. The figure shows the progression from problem-driven basic research through applied and developmental research leading to one version of the M829 series—the M829A1. It is important to note that research and development rarely proceeds as linearly and simply as the figure suggests. More often than not there are many dead ends, recursive loops, and new starts. Nevertheless, the work done in the research phase was the basis for many long-rod penetrator-related developments, such as the use of composite materials for the sabot of the M829A3 round (CTE No. 16 in the Abrams tank report). These efforts, which demonstrate the importance of basic research to providing a stream of new ideas on which to base future CTEs, involved contributions from various entities, including the Army laboratories, Department of Energy (DOE) laboratories, and academia.

[7] This definition, however, is not followed in practice. Nor should it be, according to a recent National Academies study, *Assessment of Department of Defense Basic Research* (Washington, DC: National Research Council, 2005). This NRC report recommends a concept of basic research that includes both curiosity-driven work (not addressing a particular system) and problem-driven work (applied to a particular problem or problems in developing a system).

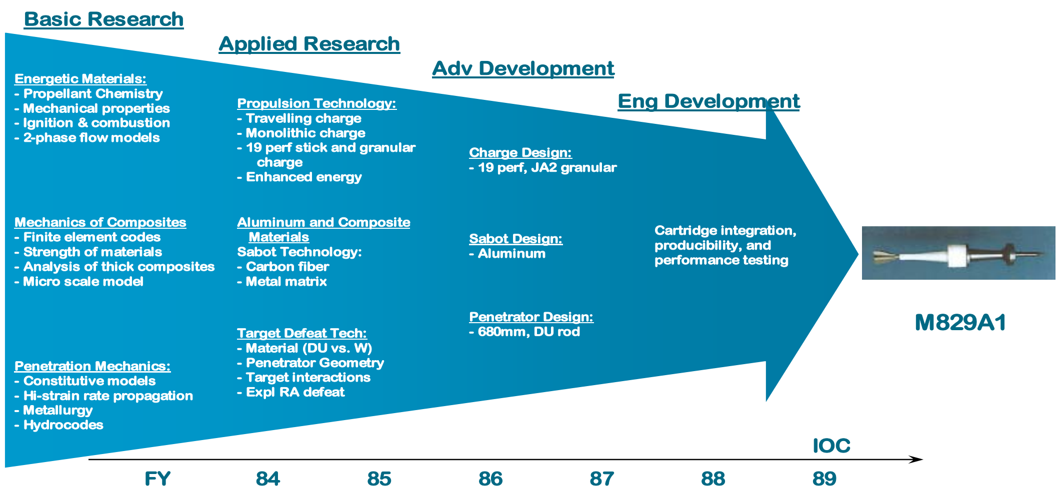

Figure 2. The evolution of a weapon from basic research to finished product.[8]

[8] From the Office of the Chief Scientist of the Army.

II. Research Results and Analysis

This chapter reviews the CTEs that emerged from the interviews and correspondence that formed the core of our research for the three *Hindsight Revisited* reports. Our study of the development of the Abrams, the Apache, the Stinger, and the Javelin yielded 134 CTEs for the four weapons systems. For each system, we offer a quick breakdown of the CTEs and a summary of our findings. We then review our analysis of an important point—the sources of the CTEs—and discuss our efforts to identify Technology Readiness Levels for the advances. Our findings and analysis for the *Hindsight Revisited* reports set up subsequent chapters, where we compare our findings with those of the original Project *Hindsight* and where we offer broad findings for all four systems and recommendations based on them.

Summary of CTEs for Four Army Weapons Systems

***The Abrams tank**…* We identified 55 CTEs in the development of the Abrams tank. The majority of these (31) were related to armor and armaments, including such advances as the 120mm gun and the composite sabot. There were 9 CTEs related to the power train and 15 related to vehicle electronics, fire control, and communications systems. As indicated earlier, not all of these CTEs were technical developments per se. Some, like the choice to use a gas turbine engine rather than a diesel engine in the tank, were managerial decisions based only in part on technology.

Our principal findings for the Abrams were as follows:

- The CTEs came from many sources inside and outside the government.
- The Army laboratories' technical expertise in armor and armaments was crucial to success. The in-house laboratories also contributed to the infrared sights, fire control systems and inter-vehicle communications system, among other things.
- The ability of Army in-house laboratories to make these contributions is attributable to the existence of a skilled technical staff with a depth of experience in the relevant technologies. It also depended on a lengthy series of Army investments in laboratory and field experimental equipment and facilities.
- Industry made essential contributions to the power train and suspension and to the development of manufacturing processes.
- Close collaboration and teamwork among the several participants, to include the Army laboratories and industry, helped move the work along. This closeness was facilitated by a supportive management at the Army laboratories.
- Integration of technologies was overseen by the PM office and implemented by the prime contractor.

The Apache helicopter… We have identified 46 CTEs in the development of the Apache helicopter. Ten of these had to do with the power system. Fourteen CTEs were related to

crew protection, an area on which the Apache's designers put special emphasis, and other structural considerations. We found 19 CTEs on the helicopter's avionics, fire control system, and weapons suite, and 3 CTEs related to the modeling and simulation work and other enabling factors.

Our principal findings for the Apache were as follows:

- Integration of the many systems and components was critical for success. This was done with oversight from the PM office and the Advanced Aviation Technology Directorate of the Aviation Systems Command, and implemented by the prime contractor.
- Teamwork was very effective. The many groups involved included the Army in-house scientists and engineers, the industrial partners, and the experts, facilities and equipment at NASA.
- Army engineers defined the needs and specifications for the Apache program and managed the program throughout. Army scientists and engineers conducted basic and applied research in support of the program. Industry engineers designed and developed key systems and components.
- Important basic and early applied research was done at co-located Army-NASA research sites. The co-location arrangement greatly facilitated work on structures, propulsion, and modeling and simulation. Use of NASA's specialized experimental capabilities facilitated the validation of models and the testing of new concepts.

The Stinger and the Javelin missiles… We have identified 35 CTEs for the Stinger and the Javelin missiles. For both systems, the emphasis is on the seeker and the guidance system. We found 6 CTEs for the Stinger's seeker and 3 for guidance and control systems. For the Javelin's seeker we found 4 CTEs, for guidance and control, 2 CTEs, and for the command launch unit, 6 CTEs. For the propulsion and warhead components we found for the Stinger 2 CTEs and for the Javelin 7 CTEs. In modeling and simulation we list 2 CTEs for Stinger and 1 for Javelin. The Javelin also had 2 CTEs that were based on early management decisions rather than technical achievements.

Our principal findings for the missile systems were as follows:

- Both missiles' development relied heavily on accumulated experience in industry with prior missiles. This was especially true in the design of the seekers, the guidance and control systems, and the propulsion motors.
- DARPA played a significant role in the Javelin program. Through a program called Tankbreaker, DARPA promoted the development of an antitank missile that would use an imaging IR seeker. It also financed the design of the two-dimensional staring focal plane arrays needed to build such a seeker.
- Modeling and simulation developed and used at Redstone Arsenal and by the prime contractor played an important role in the development of both systems. Models and simulations were used to evaluate new concepts at the laboratory stage, to predict performance in field experimentation, and for certification work.
- The PM office at Redstone Arsenal oversaw the development work and assisted the contractors in integrating the components.

- The in-house laboratories, particularly at Redstone Arsenal, the Night Vision Laboratory, and Picatinny Arsenal, made critical technical contributions. They also played an important role in evaluating contractor innovations and advising the PMs and the Army on technical issues.

Assessing the Origins of the CTEs

The CTE, it will be remembered, is a tool to identify important advances so that we can consider what factors led to the successful development of weapons systems. One crucial factor is *who* did the important S&T work. We therefore analyzed each CTE to assess who, in our judgment, was responsible for the event. We established four categories of work performers: government technical facilities, to include all government laboratories; private industry, to include prime contractors and sub-contractors; joint government/industry, for any CTE in which both government laboratories and industry played a substantial role; and other, for the accomplishments of universities and foreign governments and for CTEs that were government management decisions rather than technical advances. It is likely that no CTE represented the exclusive contribution of one of these four groups, but except in those cases where contributions were substantial enough to warrant the label "joint," we categorized the CTE based on where the clear majority of the work was performed.

The chart below contains the results of this CTE source analysis (a full list is found in Appendix A). For the Abrams, the in-house laboratories dominate with just over half of the total CTEs. If we add to this the in-house role in joint work with industry we have over 70 percent of the work involving the in-house laboratories. Around a quarter came from outside the government. The figures for the Abrams are not surprising, given the preeminent role of the Army laboratories in the areas of armor and armaments. For the Apache, the government laboratories played a somewhat lesser but still dominant role. Industry played a greater role than for the Abrams. For the missile systems, the contributions were primarily from industry; the in-house laboratories did less CTE work independent of industry. There was more collaborative or joint work in which the laboratories were important players.

System	***Gov't/In-House Labs***	***Joint***	***Industry***	***Other***	***CTE Total***
Abrams	55%	18%	13%	14%	55
Apache	43%	20%	30%	7%	44
Stinger and Javelin	17%	25%	50%	8%	35

Table 1. The percentage of the CTEs for each weapons system contributed by each source. This breakdown reinforces for us the vital role played by the government laboratories in developing the necessary technology.

Technology Readiness Levels

We also analyzed the Technology Readiness Levels (TRLs) of our CTEs. TRLs are used to assess where the technology is with respect to a development timeline. The numbers run from 1 to 9, with TRL 1 being new work and high risk, and TRL 9 being fully demonstrated in the relevant field application and ready for use in the force. The numbers can be misleading; something labeled TRL 1 may be brand new, but the path to full readiness may not be very difficult. The TRLs indicate where a project is on the path to fielding and does not tell us how hard it will be to get to the end. By assessing the TRL rating of the CTEs, we hoped to shed light on another important factor in the successful development of a weapons system: how much effort the developers should take to mature all the critical technologies with respect to the program timeline. Unfortunately, our CTE-based analysis was not well suited to drawing conclusions on TRLs

Nevertheless, we did make TRL assessments as of the beginning of work on a particular CTE. Thus, work on a technology may have just begun when work on the weapons system began. This would indicate a low TRL. If the system called for incremental improvement of an earlier technology development, then the TRL might be 5 or above. Given the lack of clear information, we made a simple determination: whether the CTE in question was TRL 5 and above, or TRL 4 and below. We choose this dividing line because TRL 5 is currently the first level at which the technology has passed the laboratory “breadboard” stage and is ready for evaluation and experimentation under relevant conditions. A CTE at TRL 4 or lower means the technology is still in the laboratory, not ready for relevant field experimentation.

The results: across the four systems, we found more CTEs with TRL levels of 4 or less than of 5 and above.[9] We were not able to address TRLs any more specifically than that. The principal complication was that the DOD only recently established TRLs as a metric, and so they were not defined explicitly in the years under study. Furthermore, though CTEs are nominally “events,” many of them refer to technologies that matured as a weapons system was developed. It was thus difficult to establish a historical point in time at which to assess the TRL, and to keep that point consistent relative to each CTE. While our findings were too general to draw useful lessons for today’s S&T program, they were broadly consistent with our CTE definition, which led us to focus on new ideas, concepts and analysis. Such a concentration on innovation meant that a majority of TRLs at 4 and below was to be expected.

[9] Please note that these estimates are the estimates of the authors, not of our interviewees or other sources.

III. Comparison of *Project Hindsight Revisited* and the Original *Project Hindsight*

The *Project Hindsight Revisited* studies were inspired in part by the original *Project Hindsight*, a Department of Defense review completed in 1969 (hereafter, DOD69). A comparison of the two studies reveals that while there are clear differences between them, their findings are largely in accord on the fundamental issue of what factors promote the development and successful utilization of defense science and technology.

The most obvious disparities between DOD69 and *Hindsight Revisited* stem from their scope and the time between them. DOD69 was a massive study of the development of 20 different weapons systems drawn from each of the military services. It involved over 100 personnel over a period of 4 years. The *Hindsight Revisited* studies looked in depth at just four Army weapons systems, and were conducted by three individuals over a year and a half. During the 36 years between when DOD69 was completed and the *Hindsight Revisited* studies were begun, clear differences arose in the way that technology is developed and fielded. The integrated circuit, the supercomputer, and the personal computer were developed during or before the development of the systems we studied. Modeling and simulation were introduced just in time for the *Hindsight Revisited* systems but were not available for the systems covered by DOD69. Further, the acquisition process was different in 1969 than it is today. Among other things, the role of Program Executive Offices (PEOs) and Program Managers (PMs) has been formalized and institutionalized.

DOD69 was driven in part by Congress, which had raised questions about the management of and overall payoff from Defense S&T spending. The study appears to be a justification of the DOD way of doing research and development. *Hindsight Revisited* focused more narrowly on the changes in performance brought about by technical advances only as compared to the technology already in the immediate predecessor weapons systems. Most of the basic science enabling these advances had been performed before the systems under study began to be developed.

Another difference between the two studies is in the two definitions of the critical events that formed the basis for their analysis. DOD69 defined a Research or Exploratory Development Event (RXD Event) as limited to the actual technical work, e.g., the conception of an idea, the design of a new component, and the initial demonstration of utility. As discussed in previous chapters, the CTE was the basic unit of analysis for *Hindsight Revisited*—we sought to determine what technical advances were important and then examine the factors that led to them. Unlike RXD Events, CTEs encompassed key technical management decisions as well as some significant technical accomplishments that were not adopted for use in the weapons system or are in versions of the system not yet fielded.

Hindsight Revisited included discussions of the in-house laboratory environment in terms of management support, funding, technical equipment and facilities and the like. We looked at the value of past investments in the technical areas and the extent to which maintaining an experienced staff is important. DOD69 did not emphasize these areas. *Hindsight Revisited* also highlighted the importance of teaming among the participants to develop technology as well as integration of the many components of a system. This was not considered in DOD69. The PEO/PM, which, as noted earlier, was introduced since 1969, had a large impact in this area.

Despite these differences, DOD69 and *Hindsight Revisited* had broadly similar objectives. DOD69 had as one of its major goals to identify management factors that will assure that DOD's "research and technology programs will be productive and that program results will be utilized." Launched with comparable objectives, DOD69 and *Hindsight Revisited* yielded similar findings. It is especially valuable to consider what the reports had to say about factors that promote the development and successful utilization of defense science and technology.

Both DOD69 and *Hindsight Revisited* found that in-house laboratories and industry made the greatest contributions to defense science and technology. DOD69 found that in-house laboratories and industry each contributed roughly 45 percent of the RXD Events, with academia and "other" making up the difference. *Hindsight Revisited*'s findings were similar, though we tracked joint government/industry CTEs while DOD69 did not consider joint RXD Events. As seen in earlier chapters, *Hindsight Revisited* found that government laboratories and industry together contributed about 90 percent of the CTEs. About 40 percent of the CTEs were attributed directly to in-house laboratories, about 20 percent were joint government/industry efforts, and about 28 percent were attributed to industry alone. The balance fell into the category of managerial decisions or contributions from allied nations and academia. Further, we found that in two systems (the Abrams and the Apache) in-house contributions were dominant; for the two missiles, industry was dominant.

DOD69 found that most new technology (as opposed to science) research in DOD's S&T program was problem-oriented, either in generic research for a group of like systems or research on problems uncovered in advanced development of a specific system. There was evidence of results developed in one program being utilized as well in related programs. *Hindsight Revisited* found that the same is true today. For example, work on infrared sensors generally applied to all four weapons systems.

DOD69 found that utilization depends on a close relationship with the user, an appropriate definition of requirements by the user, availability of talented research staffs, adequate funds, and effective communication among the participants. *Hindsight Revisited* found that this is still true today. Close working relationships among the participants were characteristic of the development of all four systems in our studies. It is hard to imagine success without such teaming and close ties

DOD69 found that the dominant technology transfer mechanism was by informal person-to-person contacts. *Hindsight Revisited* found that person-to-person contacts are very important and that there are many more ways to communicate than in 1969; e.g., the Internet for e-mail and file transfer as well as networks of scientific computers enabling teams of workers geographically far apart to carry out joint research. We also found there are many other mechanisms for transferring knowledge; namely, informal visits to other laboratories, exchange of staff for extended periods of time, permanent move of staff to another participant's operations, participation in integrated product or process teams, seminars, and technical meetings. One of the roles of the PM office is to promote such communications and transfers of knowledge

Hindsight Revisited's findings did disagree with DOD69 on one important point. DOD69 concluded that the most useful role of science (as opposed to technology) was to explain the basis of the phenomena being studied and used by the engineers, and that the engineers rely heavily on compiled scientific data in handbooks and texts. *Hindsight Revisited* found that work done in basic research does not just provide explanations for phenomena but directly supplies the foundations for the systems of interest. We also found that the basic research has usually been done well before the launch of the particular weapons program under study rather than during the development period (as shown in figure 2). Exceptions are when basic research is necessary to remove obstacles that occur during the development.

In sum, the findings of our studies substantially agreed with those of the original *Project Hindsight*. Though the technology on which it depends has evolved rapidly, the Army S&T program has consistently benefited from capable in-house laboratories and from collaboration among those laboratories, and among the laboratories, the user, and industry.

IV. Findings and Recommendations

We drew findings and conclusions on each of the specific weapons systems in our *Hindsight* reports. These were summarized in Chapter II. While each system was unique, there were common elements between our findings for each one. We have compiled these common elements, which are largely qualitative, into overarching findings. Where appropriate, we offer recommendations for consideration by the Army's S&T leadership. In the following chapter, we discuss in slightly more detail two important current issues for the Army technical community: the need to acquire and retain talented personnel for government laboratories and the adjustment to the Lead Systems Integrator approach to acquisition.

1. Funding was almost entirely from the Department of Defense.

The work on the four systems was spread over many different laboratories and over different agencies. There was some important funding from DARPA, especially in the development of the Javelin missile, but the majority of the money came from Army R&D accounts. In some cases work by contractors was done on Independent Research and Development funds, but these too come from the DOD. There were some cases where the work was done on generic technologies applicable to more than one system but still on DOD funding. There were a few areas where investments by our overseas allies produced useful additions to the systems, e.g., in the case of the Abrams, work on composite armor done by the UK, and development of the 120mm gun done by Germany.

2. In-house laboratories and industry were the primary sources of CTEs.

Although CTEs came from a variety of sources—in-house laboratories, industry, academia, foreign allies—the in-house laboratories in particular played critical roles in the development of each system. Not only did the laboratories contribute many of the CTEs themselves, but they also were partners in important collaborations with industry. The in-house laboratories played another critical role as evaluators of performance and as technical consultants to the contractors and to the Army PM office. They were able to do this because they had been able to maintain continuity of staff expertise in the important technical disciplines and had the necessary equipment and facilities. These functions helped ensure that the Army was a "smart buyer."

Industry's technical staffs, as designers of the detailed components and the final systems, and the manufacturers were at the center of these developments. They made a great many very important technical advances. In each case, they had a trained workforce, established facilities, and prior experience with weapons systems.

The same can be said of the PM office staff. Most of the staff had prior experience with similar systems. Many had worked in the in-house laboratories before taking assignments with the PM. They often had long-standing individual relationships with the contractors' staffs, relationships that facilitated collaboration.

Finally, the Army on occasion received important technology inputs from overseas allies. These resulted from long-standing agreements for cooperation between the Army and certain allied governments.

> *Recommendation A* The Army should maintain strong in-house technical expertise in critical technology areas, particularly for those in which it plays the dominant role. The in-house laboratories should be funded and managed so as to provide the capability to contribute to technical advances for new systems, to evaluate work done by contractors and to advise and consult with Army program managers and senior leadership on acquisition programs.

> *Recommendation B* While it is wise to turn to the private sector in areas where the Army has little or no expertise, the Army laboratories should maintain enough competence in those areas to adapt commercial technology for use on the battlefield. Buying off-the-shelf technology can be cost effective, but it is rarely fully ready for use in the force. The Army laboratories must remain able to act as a smart buyer, evaluating and overseeing acquisition programs.

3. Collaboration among the several participants was critical for success.

A characteristic of each development was the ability of the participants to work smoothly across organizational lines. The attitude of senior managers concerning teamwork with other entities strongly influences how the staff conducts its work. Collaboration with the private sector has long been a hallmark of Army R&D, much of it at the level of the working technologists "at the bench." There are various types of formal collaborations. Recently the Army has created large long-term centers of excellence in areas of interest to the Army for the purpose of putting more emphasis on certain technology areas and promoting collaboration between the private sector and the in-house laboratories. Some of these centers are: the Institute for Creative Technology at the University of Southern California, the Institute for Collaborative Biotechnologies at the University of California at Santa Barbara, and the Institute for Soldier Nanotechnologies at the Massachusetts Institute of Technology. These are funded with research grants to consortia of universities and private companies, and are led by universities. Another set of consortia, funded by the Army Research Laboratory (ARL) and led by industry, are more tightly coupled to the in-house laboratories. These are called Collaborative Technology Alliances. They are managed by ARL; the programs are planned by teams of people from ARL and the alliance participants; and personnel may be exchanged between the ARL and alliance members. These exchanges facilitate information flow back and forth and make technology transfer into the Army much easier.

> *Recommendation C* The Army S&T Executive should encourage and reward cooperation and collaboration between all participants. Laboratory managers should take visible steps to encourage collaboration, steps such as recognition, awards, increased responsibility, and the like.

> *Recommendation D* In those high priority areas where the private sector has more expertise than does the Army, the Army should enter into collaborative programs with the leaders in the private sector. The Army should create more of these collaborations.

4. Systems integration was key to the technology transition process.

For a weapons system to succeed the component parts must mesh smoothly. This means that each subsystem must be physically and functionally compatible with all the others. Integration was handled mostly by the PM offices and the prime contractors. We did not set out in our reports to study systems integration per se, but the topic kept coming up. It became clear that it is as important as the development of the component technologies. Integration decisions usually require tradeoffs among cost, size and weight, and functionality. To understand these factors in turn requires intimate knowledge of the needs of the ultimate user, the soldier in the field. Clearly, integration is based on detailed technical knowledge. It also requires skills in managing people and organizations. In the systems that we studied, integration was achieved by very close working relationships—sometimes continuing collaborations—among the participants. We believe these relationships account in part for the success of the programs.

Recently, the DOD has begun to use Lead Systems Integrators (LSIs) from industry to handle very large, complex systems programs such as the FCS program. The LSIs play many of the roles heretofore associated with the Army PM offices. We discuss this development at greater length at the end of this chapter.

Recommendation C also applies here—collaboration and communication between participants in the weapons development process is vital to smooth and successful systems integration.

> *Recommendation E* When the Army chooses to use LSIs it should make certain that collaboration between in-house Army experts and the contractors is required. The Army should also make sure that it receives, from its own experts, independent evaluations of the technical aspects of proposals and prototypes and advice on critical decisions involving technology.

5. The availability of a staff of highly skilled/experienced scientists and engineers was critically important.

Development was greatly facilitated by situations in which there had been a long history of technical work on the subject matter in question so that very skilled personnel were available. This was true, for example, at Aberdeen in ballistics, at the Night Vision and Electron Sensors Directorate at Fort Belvoir, at the NASA Centers, at Chrysler, at Hughes and Boeing for rotorcraft, and at Raytheon and Lockheed Martin for missiles. These groups were able to move quickly into new, related programs. One of the distinguishing characteristics of Government laboratories is their ability to sustain efforts over lengthy periods without frequent staff turnover, in contrast to the turnover in

graduate students and post-docs at universities. This stability at the in-house laboratories develops depth of expertise. The potential downside is the possibility of laboratory staffs becoming parochial; this must be guarded against. Also necessary is a management environment that is supportive and patient and champions the programs.

> *Recommendation F* The Army should make sure it maintains a technical staff based on highly qualified experts. Priority should be given to those areas in which the Army has a dominant lead in the technology over domestic industry and in which industry does not have the commercial incentive to develop a robust technology base. Examples include armor and anti-armor technologies and all weather, day/night imaging and sensor systems.

> *Recommendation G* There should be an active recruiting effort to locate talented personnel beyond the usual approaches of vacancy announcements and advertisements. The Army should use its many formal and informal contacts with the ARO-sponsored universities researchers, the Small Business Innovation Research program's work in the small business community, and contacts through collaborations at the CTA consortia and the three Institutes discussed above to attract skilled staff. There also are the on-going relations with industrial partners in systems development that could be utilized. Among other techniques, hosting exchanges with visiting scientists and engineers provides the opportunity to interest people in the challenges and opportunities of work at Army laboratories.

> *Recommendation H* The Army should provide stronger incentives to hire and retain its scientists and engineers. Salary and bonuses are important but not sufficient to keep the best research staff. Most effective researchers are motivated strongly by non-financial factors. These include: challenging work associated with an important mission, regular contacts with soldiers, stimulating colleagues, supportive management, first-class facilities and equipment, opportunities to publish, and approval to attend professional meetings. The Army should see to it that these characteristics are maintained as strong motivators for new recruits and should use the tools at its disposal (financial and otherwise) especially to keep the top echelon of its technical personnel.

6. Having the right equipment and facilities is essential to enable the technical staff to carry out the work effectively and efficiently.

Development of these weapons systems required the use of some very sophisticated research equipment, often lodged in special-purpose buildings, ranges, and the like. To take the Abrams as an example, the program called for gun ranges, armor testing ranges, special facilities for testing armor and munitions containing depleted uranium, test tracks, materials laboratories, and visualization techniques for measuring the behavior of munitions at very high speeds and during penetration of targets. It is important to note that much of the work in the four systems we studied relied on advanced computers for modeling physical phenomena; e.g., the aeromechanics of the helicopter, finite element analysis of the composite sabot for the KE rounds, and firing tests.

The Army did not develop the weapons systems we studied exclusively in its own facilities: there were important contributions from NASA and the DOE national laboratories. The co-located Army groups at three NASA sites took advantage of NASA expertise and special facilities. Most of the basic research for helicopters was done by Army staff at these NASA sites. The DOE laboratories were particularly helpful in developing the use of depleted uranium for the Abrams tank.

Army facilities are used not just by government staff but also by the contractors charged with producing a given weapons system. In particular, industry uses Army facilities for performance tests. It has long been the practice that new ground combat vehicles be tested at the Aberdeen Proving Ground, for example. Also, the test facilities and laboratories at Huntsville are used regularly by missile manufacturers.

The Army had available so many special facilities and equipment because substantial, long-term investments had been made. In some cases the facilities and equipment had been established and continually upgraded for decades—some dating from before World War II. Many of the facilities were and are unique and are used by industry in their work for the Army. The skilled staff discussed in Finding 5 were an important factor in developing and maintaining these resources. Permanent Army installations with stable staffing have enabled this expertise to build up over time and thus to take maximum advantage of the capital investments.

> *Recommendation I* To maintain in-house competence the Army must support its laboratories with appropriate facilities, equipment, staffing authorization, and funds. There must be continuity in this support: once a facility is closed it is extremely difficult to re-establish its capabilities elsewhere, both in terms of physical plant and staff.
>
> *Recommendation J* The Army should maintain its test and evaluation facilities as key parts of its development program. These should be used not only for Army activities but also by industry for tests of interim product advances to guide further development.

7. The user communities were intimately involved in development of the weapons systems.

The contributions of Fort Knox in the Abrams program and Fort Benning in the Javelin program are clear examples of the important role the user played. The user worked with the technologists to define requirements, and continuing discussions during the development phases were useful and productive. The user also defended the programs when they were in trouble; when difficulties arise that may threaten the continuance of a weapons program, the full support of the user makes a very large difference.

8. Cross-cutting Technologies.

Our studies have found many technologies that are used in more than one weapons system. The most common is the family of technologies that the military terms C4ISR (command, control, communications, computers, intelligence, surveillance, and reconnaissance). Examples of ISR are night vision sights and the Global Positioning Satellite (GPS) system. Communications networks connect soldiers to each other and commanders to their soldiers. Computers are found in all communications systems and, as microprocessors, are in nearly all weapons.

Of particular significance for systems development is the discipline of modeling and simulation or M&S. Simulation in the military falls in three categories: live, in which real people use simulated equipment in the real world; virtual, where real people use simulated equipment in a simulated world; and constructive, where everything is simulated. Simulation is used in the laboratory, in training, and in test and evaluation. As we saw in development of each of the four *Hindsight Revisited* systems, this technology enables the investigator to study many different experiments on the computer thereby expanding the scope, shortening the time, and reducing the cost of development work.

V. Concluding Remarks

We offer here two additional sets of observations stimulated by these studies. The first, on personnel policy at the in-house laboratories, presents further details on the years-long struggle at DOD to strengthen the technical staff. The second addresses the impact of using LSIs to acquire new weapons systems.

Maintaining a Strong Cadre of Army Technical Personnel

One issue that cuts across the findings given above is the importance of having relevant technical expertise, especially in the government laboratories. In recent years—since the end of the Cold War—the size of the staff at the Army laboratories has been dramatically reduced, in some cases by as much as half. Recently, due to the Global War on Terror, this trend has stopped and in some cases been reversed. Yet the question remains: how to attract and retain highly skilled personnel? This is a subject that has been studied since the 1960s. These studies cover two main categories of concern—forms of governance and personnel. These studies have been done by a variety of committees inside and outside the Army and the DOD and have produced a large number of recommendations as to how to maintain and improve the laboratories. There is consistency among the different groups: they all agree on the critical importance of having outstanding scientists and engineers and a clear and well-supported mission. Additional needs are stable and adequate funding, close relations with the user community, and champions in senior management. The recommendations for personnel include competitive pay, good equipment and facilities, challenging work, stimulating colleagues, and opportunities for interactions with the world-wide science and engineering communities.[10]

Consideration of various models of governance for the laboratories range from the status quo—government-owned, government operated (GOGO)—up to and including government corporations analogous to the Tennessee Valley Authority or the U.S. Postal

[10] Some references regarding recommended personnel practices for the laboratories are: *Report of the White House Science Council Federal Laboratory Review Panel* (Washington, DC: The White House, May 1983); *Report of the Federal Advisory on Consolidation of Defense Research and Development Laboratories* (Washington, DC: Department of Defense, September, 1991); M. L. Marshall, *The Key to a World-Class Science and Technology Enterprise: Hiring and Retaining the Best and Brightest Scientists and Engineers,* (University Park, PA: The Pennsylvania State University, Applied Research Laboratory, March 2001); J.M. Bachowsky et al, *Science and Technology Community in Crisis,* NRAC Report Number 02-03 (Arlington, VA: Naval Research Advisory Committee, May 2002); J.W. Lyons et al, "Strengthening the Army R&D Program: A Strategy for Improving Army Research and Development Laboratories," *Defense and Technology Paper 12*, (Washington, DC: Center for Technology and National Security Policy, March 2005)*;* Defense Science Board, *1987 Summer Study on Technology Base Management* (Washington, DC: Department of Defense, December 1987); Defense Science Board, *Task Force on Defense Laboratory Management Interim Report* (Washington, DC: Department of Defense, April 1994); Defense Science Board *Summer Study on Defense Science and Technology* (Washington, DC: Department of Defense, May 2002).

Service.[11] There are trade-offs in selecting the best approach. The more embedded the laboratories are in the DOD the more restricted will be the options for improving management practices. On the other hand, the further removed the laboratories are from the DOD the harder it will be to develop and maintain close relations with the user communities.

The Defense Science Board has recommended, among other things, that the DOD laboratories ought to make much more use of the Intergovernmental Personnel Exchange Act (IPA),[12] to bring in experts from state and local government (including state universities) for definite terms. Certain agencies, e.g., the National Science Foundation and DARPA, have made extensive use of this authority to develop rotating staffs, thereby bringing in diverse experiences and points of view. The Army laboratories have not made much use of this authority. The advantages of the IPA are offset by some loss of continuity and inability to develop depth of expertise. Nonetheless, more use of the IPA authority would seem to be useful, especially in areas where Army expertise is in need of rapid strengthening.

Adding visiting workers for shorter periods than for IPAs can also improve capabilities. Guests from overseas provide perspectives and ideas that may be different from U.S. approaches. In formal collaborations with the private sector, rotation of staff in and out of the laboratories can be very useful in exchanging ideas and transferring technology. The Army CTAs at the Army Research Laboratory (ARL) do this.[13]

The DOD has tried to implement some of the recommendations from the studies discussed above. Demonstrations of alternate personnel systems for the laboratories have been set up to facilitate hiring, offer employment and retention bonuses to key personnel, and link pay increases to performance. The Navy at China Lake, CA, ran a demonstration program on a number of topics for improving laboratory operations. A major part of this was a series of initiatives on personnel management; namely, classification of employees into broad pay bands and performance-based salary administration. These aspects later became the core of further demonstrations at additional DOD laboratories. Other new features included direct hiring—local authority to evaluate and classify applicants and to make job offers—for some positions. However, many of the requests from the laboratories for increased authorities have been frustrated by upper level personnel functions and the Office of Personnel Management.[14] Recently, Congress once again passed legislation in this area, requesting a detailed study of best practices in leading laboratories in the private sector and mapping those over into DOD laboratories.[15] Since the *Hindsight* studies clearly show the important role of the Army

[11] Coffey et al, "Alternative Governance: Tool for Military Laboratory Reform," *Defense Horizons Paper 34* (Washington, DC: Center for Technology and National Security Policy, November 2003); Lyons et al.
[12] Public Law 91-648, Part 334.
[13] Lyons et al.
[14] For a discussion of the experiences at innovations in laboratory management at one laboratory see Edward A. Brown, *Reinventing Government Research and Development: A Status Report on Management Initiatives and Reinvention Efforts at the Army Research Laboratory*, ARL-SR-57 (Adelphi, MD: Army Research Laboratory, August 1998).
[15] Section 1123 of the National Defense Authorization Act for FY 2006.

technical staff, the ability to improve personnel management is essential for future success. Hopefully, as the National Security Personnel System is implemented, the leadership will be mindful of these important observations.

Observations on Recent Changes in the Acquisition Process

There is no doubt that the world, and the Army's S&T needs, have changed significantly since the era when the Abrams tank was conceived. Military threats are different and the sophistication of the Army's weapons systems has increased, particularly from the introduction of advanced electronics, the changeover to digital computation, and the growing emphasis on communications technologies. As the defense community's acquisition needs have changed, so have the ways in which technology development programs are carried out. Collaboration with the private sector is the order of the day. Among other things, the Army has set up formal collaborations, such as the CTAs described in Chapter IV, wherein the Army technologists and their industrial and academic partners jointly plan and execute programs in basic and applied research.[16] This shift toward a greater utilization of private sector resources is driven in part by fact that the private sector has overtaken the DOD technology base in some areas, including electronics, computers, and software. Also, new weapons systems incorporate a broader range of technologies and are generally more complex than in the past, so it behooves DOD to call on all the resources available.

The cardinal example of the trend toward ever more complex weapons programs is the Army's Future Combat Systems (FCS). In brief, FCS is a family of 18 manned and unmanned weapons and air and ground platforms, bound together by a network, that will provide the backbone of the Army of the future. The cost of developing and procuring FCS is currently estimated at $160B.[17] The DOD has turned to outside firms to manage this massive program (and others) and oversee integration of the many parts. For FCS, this function, called Lead Systems Integration (LSI), is being fulfilled by Boeing and Science Applications International Corporation (SAIC). This new acquisition strategy vests significantly more responsibility in private industry than was previously the case.

Though the world and the Army's needs have changed, one point made apparent by the *Hindsight Revisited* studies should not be lost: the Army has had significant success in the past decades in developing new, formidable weapons systems. In particular, our *Hindsight Revisited* reports clearly indicate that the government laboratories are a vital resource in weapons development. This resource must be used effectively in the new regime. The challenge is to achieve close collaboration between in-house experts and contractors and to obtain the independent judgments needed to evaluate proposed innovations by the contractors and to advise the Army acquisition community on

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[16] Brown.

[17] Paul L. Francis, "Defense Acquisitions: Business Case and Business Arrangements Key for Future Combat System's Success," testimony before the Subcommittee on Airland, Committee on Armed Services, U.S. Senate, 1 March, 2005, GAO-05-44-2T (Washington, DC: Government Accountability Office, 2005).

technical aspects important to their decision making. In an effort to see the impact of this new way of doing acquisition on the in-house laboratories, we have taken a brief look into the FCS program by interviewing eight senior individuals from across the Army's laboratories. We were particularly interested in the nature of and extent of collaboration among the different players as compared to what we have seen for the four weapons systems in the *Hindsight Revisited* studies.

The Army manages the FCS program through the FCS Brigade Combat Team Program Manager (PM FCS BCT), who is teamed with the LSI (Boeing and SAIC). The LSI has responsibility and accountability for managing and executing the program and making day-to-day decisions on technical matters. However, the PM FCS BCT is the final authority. Since FCS relies heavily on new or emerging technologies to meet the operational requirements, there has, from the outset, been a close cooperation between the Army S&T community and the PM FCS BCT/LSI team. The concept phase of FCS (2001-2003) was solely funded by a combination of Army S&T and DARPA funds. Once FCS became an acquisition program, after the approval of the program's Milestone B in 2003, the System Development and Demonstration phase of the program had its own dedicated funding. Since that time, the job of maturing and demonstrating the requisite technologies has been funded either by Army S&T, by the FCS program itself, or through a DARPA/Army S&T collaboration. From 2003-2006, the majority of the Army's 6.2 and 6.3 budget was used to fund maturation and demonstration of high priority technologies in the in-house laboratories. Both the PM FCS BCT and the LSI were participants in managing the S&T programs so as to align them with the FCS goals and objectives. In most cases, the Army laboratories did not receive funding directly from the FCS program or from the LSI or its subcontractors. The FCS program did provide direct funding to the in-house laboratories for labor and technical support, such as serving on integrated process teams (IPTs) and source selection boards.

As FCS moves forward, the task of transitioning the technologies that have been matured and demonstrated has become a priority issue and is being addressed through formal Technology Transition Agreements between and among the participants. Once mature technologies are successfully transitioned, the development and demonstration of prototype systems will be solely funded by the FCS program. In cases where this development activity will need to be supported by in-house technical experts, the FCS program will provide funding.

In general, these arrangements seem to be producing effective utilization of in-house expertise, especially in niche areas such as armor, armaments, and ground combat vehicle chassis. Collaboration among the participants appears to be as strong as under the earlier management approach. Some in-house participants said that they are very close to the private sector subcontractors and to the LSI. We are told that the technical staff are stimulated by the challenges of the FCS program. If they are having difficulties it seems to come from the sheer size of the FCS program and the corresponding size and complexity of the management offices, including both the PM FCS BCT office and the LSI offices.

Further changes in the Army S&T program have also been beneficial. At about the same time the FCS program was established, the Army Materiel Command (AMC) established the Research, Development, and Engineering Command (RDECOM) to manage AMC technical work. To improve collaboration and integration, RDECOM has set up two new mechanisms: IPTs and technology transition agreements (TTAs). These are meant to draw together the players in planning and execution such that the work is synchronized in terms of technical content and timing. RDECOM is institutionalizing matters and relationships that used to be left to individual players. Reaction to this at the RDECs and ARL seems to be positive.

In general, recent changes in the acquisition process and in Army S&T management seem to be working well, at least from the point of view of the laboratories. However, one result of the FCS program has been a narrowing of focus of the laboratories. The tech base support they receive is for work in overcoming technical barriers in the FCS program. One gets the impression that there is less flexibility and less long-term innovative work going on. We believe that the Army S&T Executive should monitor this aspect closely.

Conclusion

Our studies of the role of technology in the development of Army weapons systems have shown that there are, in every success story, strong, constructive interactions between the Army's in-house laboratories and the technical staffs of the industrial contractors. This collaboration has sometimes been assisted by contributions from other Government laboratories, universities, and our overseas allies. However, the main players have been the Army laboratories and industry, operating under the oversight and participation of the PM offices. We conclude that for future success the Army in-house laboratories must be supported by sufficient, funding, strong leadership, and top flight technical staff. To accomplish this will require champions at all levels in the Army and in DOD. The Congress has shown its willingness to help in the personnel area. We have offered suggestions as to the measures required to maintain and strengthen these laboratories. We believe strongly that such steps will go a long way to ensuring the continued effectiveness of the Army's warfighters.

Appendix A: CTE Sources

Abrams

		Gov't/In-House Labs	Joint	Industry	Other
	Armament Related CTEs				
1	120mm gun decision				X
2	Fracture mechanics application	X			
3	Swage autofrettage process	X			
4	Error budget	X			
5	Statistical models	X			
6	Gun tube straightening process	X			
7	Long-rod penetrators/120mm gun decision				X
8	Long-rod penetrator development	X			
9	Long-rod penetrator modeling	X			
10	Depleted uranium LRP decision				X
11	High rate forming DU process				X
12	Penetrator/target interaction analysis	X			
13	Slipping rotating band	X			
14	Sabot tipping ring and scoop design	X			
15	Aluminum sabot technology	X			
16	Composite sabot technology		X		
17	Propellant modeling and analysis	X			
18	Propellant design and development	X			
	Armament Subtotals:	13	1	0	4
	Armor and Other Survivability Related CTEs				
19	Hull design and analysis	X			
20	Hull joining technology	X			

21	U.S/U.K armor technology exchanges				X
22	Special armor design	X			
23	DU armor application		X		
24	Ammunition compartment design	X			
25	Less sensitive munitions	X			
26	Ammunition sensitivity test rig	X			
27	Combustible casings		X		
28	Fire protection system		X		
29	Nuclear, Biological and Chemical protection system		X		
30	Predictive computer models for live-fire tests	X			
31	Robust model for live-fire tests	X			
	Armor Subtotals:	8	4	0	1
	Engine and Drive System CTEs				
32	Gas turbine engine decision				X
33	Gas turbine engine development			X	
34	Air filtration system			X	
35	Hydromechanical transmission			X	
36	X1100 transmission requirements and decision				X
37	X1100 transmission gears and brakes			X	
38	Improved suspension system			X	
39	Replaceable track pad		X		
40	Drive sprocket fix		X		
	Mobility Subtotals:	0	2	5	2
	Vetronics, C4ISR, and Fire Control CTEs				
41	Vetronics digital architecture		X		
42	Army Science Board concept				X
43	The Intervehicular Information System (IVIS)	X			
44	Position/Navigation system	X			

45	Intercom system	X			
46	Force XXI Battle Command, Brigade and Below	X			
47	Common module approach	X			
48	Models to predict Minimum Resolvable Temperature	X			
49	Commander's Independent Thermal Imaging System		X		
50	Digital fire-control system		X		
51	Laser rangefinder	X			
52	Eyesafe laser rangefinder			X	
53	Muzzle reference system	X			
54	Muzzle reference system fix	X			
55	Digital ballistic computer			X	
	C4ISR Subtotals:	9	3	2	1
	ABRAMS GRAND TOTAL	30	10	7	8

Apache

		Gov't/In-House Labs	*Joint*	*Industry*	*Other*
	Power System CTEs				
1	AATD sets engine requirements				X
2	Simplified combustor design			X	
3	Particle separator design			X	
4	Re-design to reduce vibration of compressor blades			X	
5	Blisks			X	
6	Ceramic coating	X			
7	Rare earth magnets				X
8	Incremental T700 improvements			X	
9	Run-dry transmission			X	
10	Gear technology advances	X			
	Power System Subtotals:	2	0	6	2

	<u>Crew Protection, Survivability, and Structural Considerations CTEs</u>				
11	Priority placed on crashworthiness				X
12	Crash survival design guide	X			
13	Crashworthy fuel system		X		
14	Wire-strike protection	X			
15	Transparent armor to separate cockpits	X			
16	Improved armor for seats		X		
17	Active and passive survivability measures	X			
18	Load-bearing armor		X		
19	Composite materials for rotor		X		
20	Ballistically tolerant rotor blade		X		
21	Analysis of delamination process in composite materials	X			
	Survivability Subtotals:	5	5	0	1
	<u>Avionics, Fire Control, and Weapons CTEs</u>				
22	TADS/PNVS			X	
23	FLIR performance model	X			
24	High-resolution FLIR for TADS	X			
25	Pilotage-optimized FLIR for PNVS	X			
26	Head mounted site for IHADSS	X			
27	Symbology for IHADSS	X			
28	Protocols and design standards for IHADSS symbology	X			
29	Model for rotorcraft ballistic fire control	X			
30	Computerized fire control	X			
31	1553 databus			X	
32	Radio Frequency Interferometer			X	
33	Improved data modem		X		
34	Early rotorcraft targeting radars		X		
35	Longbow MMW radar			X	
36	MIMIC	X			
37	Mast-mount for Longbow	X			

38	Aerodynamic studies for mast-mounted Longbow	X			
39	SAL seeker for Hellfire		X		
40	Longbow Hellfire			X	
41	30mm chain gun			X	
	Avionics Etc. Subtotals:	11	3	6	0
	Modeling and Simulation and Other Enabling Methodologies CTEs				
42	Modeling to prevent structural failure due to vibration	X			
43	Engineering Design Simulator			X	
44	Rotorcraft Pilot Associate program		X		
	Methodology Subtotals:	1	1	1	0
	APACHE GRAND TOTAL	19	9	13	3

Stinger and Javelin

		Gov't/In-House Labs	*Joint*	*Industry*	*Other*
	Stinger Seeker				
1	Conical scanning			X	
2	Rosette scan seeker			X	
3	IR/UV detector			X	
4	Seeker microprocessors	X			
5	Reprogrammable microprocessor			X	
6	Lithium battery	X			
	Stinger Seeker Subtotals	2	0	4	
	Stinger Guidance and Control				
7	Canard servomechanism			X	
8	Laser ring gyros			X	
9	Terminal adaptive guidance		X		
	Stinger Guidance and Control Subtotals:	0	1	2	

	Stinger Propulsion and Warhead				
10	HTPB propellant binder	X			
11	Propellant case bonding			X	
	Stinger Propulsion and Warhead Subtotals:	1	0	1	
	Stinger Modeling and Simulation				
12	Computer-based simulation		X		
13	Hardware-in-the-loop simulators		X		
	Stinger Modeling and Simulation Subtotals:		2		
	STINGER SYSTEM TOTAL:	3	3	7	
	Javelin Background				
14	Tankbreaker funding decision				X
15	Javelin Joint Venture decision				X
	Javelin Background Subtotals:	0	0	0	2
	Javelin CLU				
16	CLU long-wave imaging IR			X	
17	CLU bi-directional scanner			X	
18	CLU Thermal Reference Assembly			X	
19	CLU cooling system design			X	
20	CLU system improvements			X	
21	Composite housing		X		
	Javelin CLU Subtotals:	0	1	5	0
	Javelin Seeker				
22	Army fire-and-forget requirement				X
23	Seeker focal plane array		X		
24	Hughes FPA design			X	
25	Seeker calibration "chopper wheel"			X	
	Javelin Seeker Subtotals:	0	1	2	1
	Javelin Guidance and Control				
26	Tracker			X	
27	Captive flight testing		X		
	Javelin Guidance and Control Subtotals:	0	1	1	0

	Javelin Warhead and Propulsion				
28	Integrated propulsion design			X	
29	Launch motor shear pins		X		
30	Burst disc			X	
31	Tandem shaped charge warhead	X			
32	Precursor charge design			X	
33	Blast shield	X			
34	ESAF	X			
	Javelin Warhead and Propulsion Subtotals:	3	1	3	0
	Javelin Modeling and Simulation				
35	Integrated flight simulation		X		
	Javelin Modeling and Simulation Subtotals:	0	1	0	0
	JAVELIN SYSTEM TOTAL:	3	5	11	3
	MISSILE GRAND TOTAL	6	8	18	3